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Stability and design criteria for CICC with a broad transition to normal state

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Abstract

Stability in cable-in-conduit conductors (CICC) against perturbations is often associated with transient heat removal of heat generated in the normal zone. Based on this approach, stability criterion requires low current density in the strands. This criterion is often used for design of the magnets for fusion devices like ITER, KSTAR and others. We show that this criterion is not a mandatory requirement for serviceability of CICC and that CICC may work reliably at higher current densities. In conditions of limited and well defined perturbations, sufficient stability is provided not by a large amount of copper and high transient heat transfer, but by a smooth transition to the normal state and easy current redistribution. A strand parameter space in terms of I_c and N-value meeting CICC requirements for stability, limited heat generation, and minimum temperature margin is proposed and discussed. The theory predictions are compared with known experimental data on CICC.

Keywords: Key words: Cable-in Conduit, Critical current, N-value, stability

Introduction

We will call a perturbation “strong” when a local normal zone appears and a significant fraction of current is expelled into the copper stabilizer. In such a transient condition, a simplified approach to stability of CICC based on the Stekly criterion [1] calls for a sufficient amount of copper in the strands, of sufficiently small diameter, such that the heat removal is higher than the heat generation:

$$\alpha = \frac{I_c^{\,2} R}{hP(T_c(B) - T_b)}; \quad \alpha \left(\frac{I_{\lim}}{I_c} \right)^2 < 1 \qquad (1)$$

where $I_{\lim}$ is the maximum stable operating current, R is the resistance in the normal state, h is the heat transfer coefficient, P is the cooled perimeter, $T_c(B)$ is the critical temperature in the given magnetic field, T_b is the background temperature. This parameter initially introduced for bath-cooled superconductors [1], had a large influence on the success of large-scale applied superconductivity. When internally cooled conductors came into play, first, the monolith conductors with cooling channels and later, CICC, criterion (1) was still used for design, although the heat transfer coefficient was found to depend on transients like induced flow and thermal diffusion. To find an effective “integrated” heat transfer coefficient, a statistical study was carried out about performance of many CICC magnets [2], and it was found that most of the magnets reached their “limiting” currents, defined by criterion (1), if the effective heat transfer coefficient is assumed between 400 W/m^{2}K and 1400 W/m^{2}K.

Such a large scatter shows that criterion (1) is not an accurate criterion when applied to CCIC; it is just a favorable condition to utilize enthalpy of helium in so-called "well-cooled' regime. As a consequence, the violation of this criterion does not necessarily make the CICC inoperable, and vice versa, complying with the criterion does not guarantee absence of quenches. A mechanism, which may quench a stabilized CCIC is a non-uniform current distribution. If current transfer is not easy, one of the strands develops a normal zone, the normal zone may grow until it consumes all available helium enthalpy. In this case, recovery is impossible, and the conductor quenches even if criterion (1) is fulfilled. There have been few cases where magnets with such a design basis have quenched prematurely due to stability reasons (for example, MIT 27-strand sample [3], DPC-U1 conductor with insulated strands [4]).

Criterion (1) applied to CICC in the conditions with high dB/dt also does not guarantee stability. After the US DPC experience, where criterion (1) was not fulfilled and a noticeable ramp rate limitation was observed [5], it was suggested that compliance with criterion (1) would eliminate the ramp rate sensitivity. However, the CS Model Coil, designed in accordance with (1), had about the same sensitivity to the dB/dt [20] as US-DPC. For both conductors, the ramp rate sensitivity became apparent at dB/dt higher than 0.6-1.2 T/s. Thus, compliance to criterion (1) did not guarantee a better ramp rate limitation for CSMC.

The experiments on the segregated copper [7] showed that performance of conductor-B was stable against quite strong perturbations at significantly higher than the limiting current, and there was no sign of dramatic improvement in performance below I_{lim}.

How essential is criterion (1) for the CICC design? It is well known that high density magnets, like accelerator magnets do not use it, since criterion (1) demands quite a low current density. It was shown in [8-10] that another mechanism of stability against small perturbations comes from a smooth transition into the normal state.

Stability criterion against small disturbances for CICC

The stability of the superconductor against small perturbations is determined by the quasi steady state equilibrium between the heat generation and heat transfer [8-11]. The solution is: the system is stable if the electrical field in strands does not exceed electrical field in strands at takeoff :

$$E < E_{to} = \frac{hPT_o}{I_{to}} \tag{2}$$

where E_{to} is the takeoff (or thermal runaway or quench) electrical field, and I_{to} is the takeoff current, found by iterations. For the equation of the superconductor properties we use [12]:

$$E = E_c \exp\left(\frac{I - Ic(T_{sc}, B_{sc})}{I_o} + \frac{T - T_{sc}}{T_o} + \frac{B - B_{sc}}{B_o}\right) \tag{3}$$

which within 2-3 orders of magnitude, is practically indistinguishable from another, empirical approximation, $E=E_c(I/I_c)^N$, in which the N-value defines the smoothness of the transition. Here T_o, I_o, B_o are growth parameters for temperature, current and magnetic field, respectively, and the subscript "cs" indicates current sharing parameters at which $E=E_c$ ($I=I_c$).

The meaning of criterion (2) is that until the electrical field in the superconductor reaches the takeoff field as a consequence of operations or perturbations, the superconductor is stable, regardless of what caused the elevated electrical field in the first place (e.g., high current density, temperature rise, pulsed heat, varying magnetic field or high rate of current charge). At a constant heat transfer coefficient, the takeoff will take place at strand overheating above the local helium temperature by T_o (typically 20-50 mK for NbTi and 0.1-0.4 K for Nb3Sn) regardless of the value of the coefficient. Since during current charge or relatively slow varying field the disturbance does not represent a fast transient event that would trigger fast thermal conduction into helium (so called transient heat transfer, typically much higher than the steady state heat transfer to helium), formula (2) uses the steady state heat transfer coefficient, not the transient one. Therefore, formula (2) is the stability criterion against small perturbations. Small perturbations never exceed the threshold of the stable electrical field (the takeoff field). In contrast, strong perturbations bring the conductor well above stable electrical field and result in either recovery or normal zone propagation depending on the heat removal conditions. Strong perturbations must be short in time to have a chance of recovering; small perturbations could be long or continuous in nature.

Effect of copper stabilizer in the strands

Since there is an economic incentive to remove copper from the strands and place it in pure copper strands for protection, we will discuss the role of copper for stabilities against small disturbances. This solution (2) is valid when differential resistance of the composite superconductor (dE/dI) is much less than the resistance of the shunting copper R_{cu}. In many practical cases of CICC this is true. Let us make some estimates. For example, if we take a Nb3Sn composite strand 0.8 mm in diameter with Cu: nonCu ratio of 1:1, jc(nonCu)=650 A/mm^2, N=20, ρ_{Cu}=5e-10 Ohm*m, and takeoff electrical field E_{to}=1 mV/m, then R_{Cu}=1.6e-3 Ohm/m and dE/dI = E_{to}/Io=E*N/I_c=1e-4 Ohm/m. In other words, in these conditions the effect of electrical shunting by copper on stability is negligible. Even without copper, superconducting strands still have some finite stability margin. However, copper resistivity can become important at lower current density. A simple parallel connection of superconductor and copper will take this into account [13].

Criterion (2) predicts that the electrical field of takeoff is inversely proportional to the current carrying capacity of the strand. This effect could explain the observed difference in stability of two CICC with the same current carrying capacity but different strands [7] under AC conditions. CICC-A had all strands identical, CICC-B had a mixture of the same diameter superconducting strands with higher content on Nb3Sn cabled with pure copper strands. Both CICC-A and CICC-B had identical amount of copper and I_c. Under the AC field, CICC-B showed noticeably lower stability despite the same temperature margin and lower losses than in CICC-A, possibly because the varying field not only generated losses but also generated high electrical fields in the strands by inducing high shielding currents. Due to higher Ic in the strands and lower electrical field of takeoff in CICC-B the varying field could have made it less stable against pulsed magnetic field. This mechanism is different from the idea that the segregated copper does not participate in stability of the strands. Copper is still needed in the strands in the CICC to ensure good thermal conductivity and heat transfer with helium.

The optimum amount of copper in the strands can only be defined if the perturbations and distribution of electrical fields and currents in the strands are known. In reality, this is rarely the case, so the selection of the required copper content in the wire for a particular application needs to be found experimentally.

What do we need to know for optimum design of the superconducting transition

Suppose we want to design an optimum CICC. What transition to normal state would we consider "optimum" for strands, which the cable is made of? If we know strand properties in the CICC, the perturbations in the magnet, operating conditions and can express them in terms of electrical field in the strands in CICC, then we should be able to determine how smooth the transition needs to be, how much copper is required, and what wet perimeter is needed for stability against these perturbations. (Other factors, such as protection during the energy evacuation, should be considered as well and may or may not be a design driver, but that is beyond the scope of our discussion here.)

It is not an easy task to translate perturbations into electrical fields in CICC. Even if the magnetic field distribution is known, it is not easy to determine the maximum electrical field in the strands of the CICC, due to complexities of the cable geometry, uncertainty in exact locations of particular strands, and contact resistances between strands. Mechanical disturbances are also poorly defined and may constitute a problem if the strands are not well supported or the conditions for current distribution are not good. Therefore at this stage, theoretical computations have limited prediction power and serve only as guidance that cannot replace experimental verification.

Typically, smoother transitions have lower I_c. Fig. 1 illustrates possibilities, showing Volt-Ampere Characteristic (VAC) with increasingly inhomogeneous superconductor. The inhomogeneity causes a little lower critical current, but results in significantly higher the takeoff voltage, which means higher stability.

The task of defining the acceptable conductor parameter's space was first formulated for the T-15 tokamak conductor [14] by taking into account a limited heat generation and a guaranteed temperature margin. If there was heat deposition in the conductor, it would have enough temperature margin to withstand it, and simultaneously, the steady state heat generation would be acceptably low. In this paper we add the requirements that the strand would have a relatively high takeoff electrical field for high stability.

Suppose that we know the current and electrical field distribution in the strands. Then from the equation (2) we can calculate required smoothness to maintain the

CICC stable. What is the most dangerous perturbation for ITER conductors? It is thought to be plasma initiation and disruption. Other perturbations (like mechanical motion, epoxy cracking, micromotion of the turns) were not seen to be a factor in recent tests of the Model Coils. When a time-changing magnetic field is imposed on a CICC, shielding currents are induced in the cable. Figure 2 shows schematically two strands, carrying currents I1 and I2, respectively, connected through the contact resistances R. These resistances are not necessarily equal to each other, and in the joints at the end of the conductors the resistances between the strands are the lowest. A loop with a certain area S is formed between the two contacts, linking a variable flux S(dB/dt). We may write a Kirchhoff rule for this loop as:

$$S\frac{dB}{dt} = \int E_1 dl - \int E_2 dl + 2I_n R + \sum L_i \frac{dI_i}{dt} \tag{4}$$

The left hand side term denotes the electromotive force, including external magnetic field and the field generated by other loops near the loop in question. The two first terms in the right hand side of the equation denote the voltages between the contacts developed along the strand 1 and 2, respectively. The third term accounts for the voltage across the contacts and the last term represents the sum of the inductive terms from the cable strands.

To determine local current distributions we need to write the equations for all independent circuits in the cable, add boundary conditions at the joints, and solve them. Suppose we develop an accurate model to find the solution. Let us discuss what qualitatively we would expect to see.

The induced shielding currents flow in the strands and close in the loops through the contacts between the strands, including contacts in the joint. These shielding currents are superimposed on the transport currents, and this generates or enhances an existing non-uniform current distribution in the CICC. When the transport current is low and the rate of varying magnetic field is low, the loop currents are small and do not push transport currents close to the local critical current. The loop currents, closing through the contacts between the strands, generate coupling losses, which increase helium background temperature and local temperatures of the strands in the points of contact. The flux change is balanced by the voltage drop across the contact resistance and electrical field in superconducting strands is negligible. As the transport current increases, and/or rate of varying field grow, the current in some strands approaches to the local critical current and starts generating electrical field in the strands. If this electrical field exceeds the electrical field of takeoff in some strand, the strand quenches and may quench the whole cable if transport current is high enough. Thus, to withstand the varying magnetic field, we need to use the strands that have a takeoff electrical field that is higher than the anticipated maximum electrical field that can be developed in the CICC under varying magnetic field conditions.

The typical current charging rates in tokamaks, plasma initiation, and plasma disruption result in field variations below 1-10 T/s. There are two possible causes of quench. First is associated with losses, mostly in contacts and hysteresis, which increases the helium temperature above current sharing temperature. In this case the quench current is close to the critical current at the local helium temperature. The second is when shielding and the transport current in a strand exceeds the I_c and in this case the CICC transport current is lower than I_c at the local temperature. This case is the instability problem and can be cured by higher E_{to}. For example, tests of ITER Central Solenoid Model Coil and the Central Solenoid Insert showed that they could reach the expected critical currents at their corresponding elevated temperatures due to AC losses up to about 0.6 T/s and 1.2 T/s, respectively [6]. Only above those rates, the stability became the limiting factor and quench occurs at operating currents below critical. That shows that stability against varying magnetic field is not the only limiting factor for CICC operation; the other factors should be taken into account for design when analyzing the serviceability limits. If heating due to losses is the limiting factor, a low N-value of the strands is not as important as a temperature margin. If stability is the limiting factor, lowering N-value can improve the limits of serviceability but will also increase heat generation at the steady state.

Let's try to find an area of acceptable parameters for a strand in Ic and N-value coordinates for ITER TF cable operating in conditions given in Table 1. The requirements we impose on the cable are: minimum temperature margin of 0.7 K, maximum allowable heat generation at peak field of 500 W, and minimum electrical field of takeoff in the strand of 1 mV/m at maximum operating current. As one can see we replaced a requirement of being stable against particular pattern of the varying field with requirement of minimum electrical field of takeoff. To describe the strand properties in the CICC we use Summers' correlation with the following parameters: Bc20m=32 T, Tc0=17.2 K, Co and N-value were variables to satisfy the constrains.

For heat generation calculations we assumed that only the innermost TF conductors in the straight leg, first layer generate the heat. There are a total of 12 conductors per coil, which are located in the high field area. The length of the conductor in high field area was assumed to be 10 m. Since there are 18 coils, the total heat generating length in the TF system is 2160 m.

Fig. 3 shows the area of acceptable parameters satisfying constraints of the temperature margin, electrical field of takeoff and limited heat generation at the operating current and at operating temperature.

At high N-values, the critical current of the strand obviously must be above the critical current, but cannot be too high since the electrical field of takeoff is too low to withstand fast varying magnetic fields inducing high electrical fields in the strands. This is a counter intuitive conclusion where too high Ic at high N could be a reason for instability. This is similar to the flux jumps phenomenon in filaments when the high jc is the main reason of instability.

At low N-values the limitation on Ic is not so severe, since the electrical field of takeoff is high, but the critical current must be higher than for a high N-value due to high heat generation at steady state operating conditions. In other words, below a certain N-value, the limiting factor is not the temperature margin, but heat generation in the conductor. Given the choice, it would be most practical to select the Ic and the N-value to be in the lower right corner in the space of acceptable parameters in Fig.3, since that would give a low heat generation in the steady state conditions and would require a lowest cross section of superconductor to provide necessary Ic to satisfy a given temperature margin. In reality, however, the real Nb3Sn CICC show N-value of 7-10 [6], which means that the only realistic constraint comes from temperature margin and at lower than N=5 – from excessive heat generation; the stability requirement is easily fulfilled. This Fig. 3 shows that higher critical current and high N value do not necessarily give a CICC better performance, since high shielding currents, can initiate premature quench.

Summary

It is shown that the Stekly type criterion (1) in CICC cannot be considered mandatory for stability. Therefore, it may be justified to go for higher current density in the design, if there is a significant benefit to it, but it is necessary to verify the conductor performance experimentally.

A smooth transition provides the stabilizing effect for CICC. Although understanding of stability due to smooth transition allows explaining some experiments, where stability is involved, the quantitative predictive power of this understanding is not well developed as a practical design tool yet. To make such a tool, we need to know possible perturbations in the magnet and then develop ways to translate these perturbations in electrical fields along the strands. Until such tools are developed, we have to rely on approximations and correlations and heavily rely on the full scale testing in our effort to design magnets with predictable performance.

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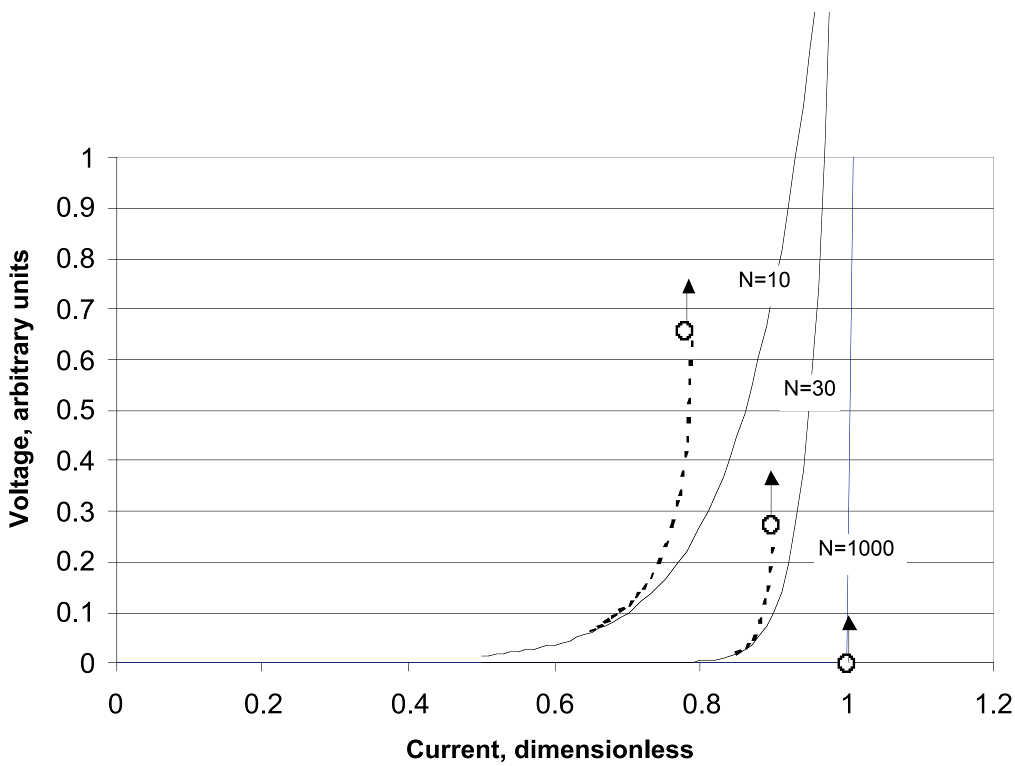
Fig. 1. VAC curves for different N-values, for both idealized isothermal (solid lines) and real temperature (dashed lines) curves. The circles show the takeoff points.

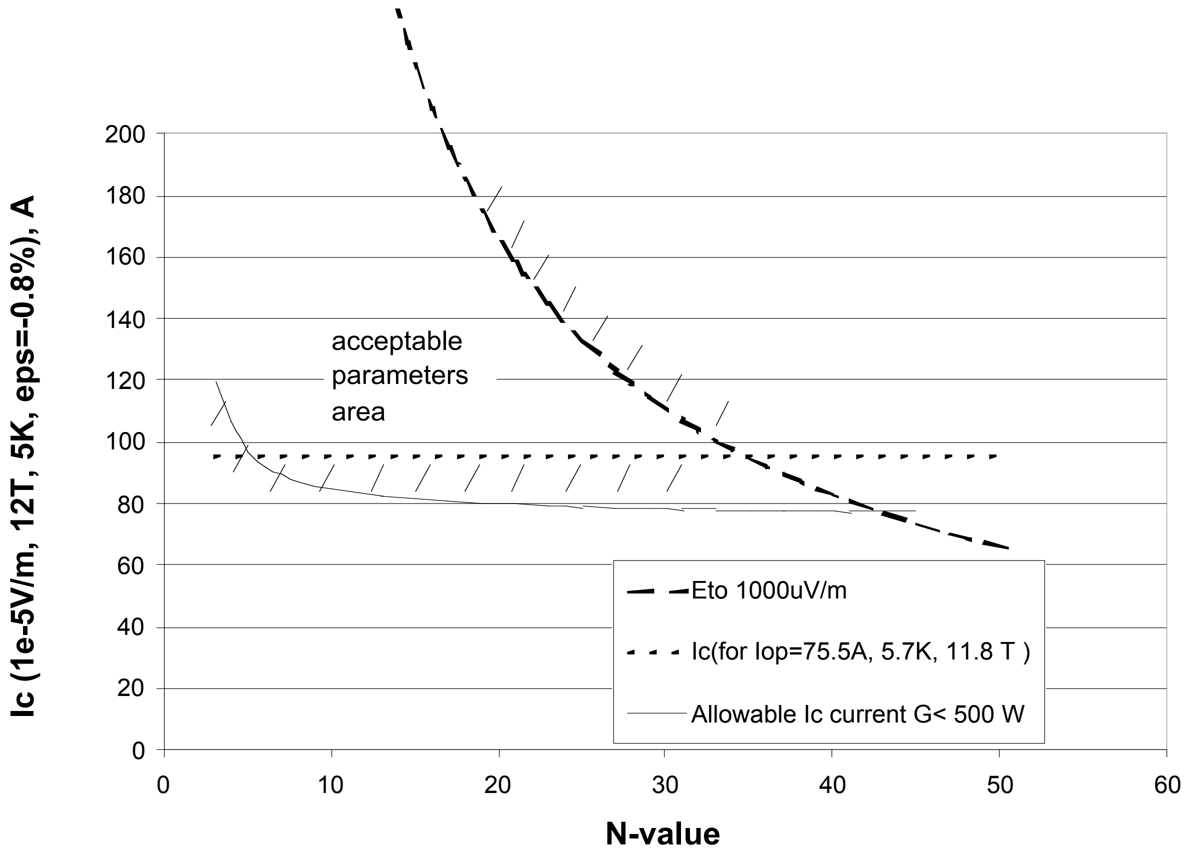
Fig. 2. Schematic loop in a CICC exposed to a variable magnetic field

Fig. 3. Area of acceptable parameters for a strand to be used in the ITER TF CICC



N. Martovetsky Fig.1. VAC curves for different N-values, for both idealized isothermal (solid lines) and real temperature (dashed lines) curves. The circles show the takeoff points.

N. Martovetsky Fig.2 Schematic loop in a CICC exposed to a variable magnetic field



N. Martovetsky Fig. 3. Area of acceptable parameters for a strand to be used in the ITER TF CICC

Table 1. ITER TF cable parameters.

Parameter	Units	Value
Operating temperature, Tb	K	5
Operating magnetic field	T	11.8
Number of SC strands		920
Operating current	kA	68
Heat transfer coefficient	W/m^2K	400
Operating strain	%	-0.8
Strand diameter	mm	0.8